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Effects of Design Speed and Normal Acceleration on Aircraft Structure Weight

by

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Effects of Design Speed and Normal Acceleration on Aircraft Structure Weight

by

M.E. Burt, B.A., A.F.R.Ae.S.

SUMMARY

Graphs show the structure weight of typical fighter and bomber aircraft for ranges of design diving speed and maximum normal acceleration. Variations of wing loading and geometry, and the use of spar or box-beam wing construction are investigated.

The calculations of structure weight are based upon methods developed at the R.A.E.

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1 Introduction

The specified values of design diving speed and maximum normal acceleration form the foundation of aircraft strength and stiffness requirements, and thus affect both airworthiness and structure weight. The aim of this report is to give a general picture of their effect on structure weight for use in project investigations.

Graphs show the structure weight of typical fighter and bomber aircraft for ranges of design diving speed and normal acceleration, at several values of wing loading, aspect ratio, thickness/chord ratio and taper ratio. Changes in structure weight for various conditions are deduced. The effects of aircraft size and of spar or box-beam wing construction are considered. The effects of wing sweep-back are also considered.

The calculations of structure weight are based upon methods developed at the R.A.E. and are described in an Appendix. Similar graphs may be constructed for cases not covered by this report.

2 Procedure

The structure weights of two "standard"* aircraft, a fighter and a bomber, are calculated for ranges of design diving speed and factored maximum normal acceleration coefficient. The calculations are repeated with alternative values of some characteristics which may vary and alter the structure weight. These are wing loading, aspect ratio, thickness/chord ratio, taper ratio and sweep. The standard values, and the other values investigated, are listed in Table I.

All aircraft are assumed to be of conventional aluminium-alloy construction. Two types of wing construction are investigated. First the "spar" type for which the material providing bending strength is concentrated in spar flanges, and is separate from the cover material which provides torsional stiffness. The second is the "box-beam" type for which the material providing bending strength is distributed along part of the top and bottom surfaces, so that the same material provides both bending strength and torsional stiffness.

The total structure weight is given by the sum of wing, fuselage, tail unit and undercarriage structure weights. The calculations of component structure weights are based upon methods developed at the R.A.E.[1,2,3]. Details are given in Appendix I.

The aircraft investigated are described throughout as the "fighter" and the "bomber", but the graphs represent the trends for aircraft with any duty whose characteristics are similar to those assumed. In particular the curves derived for the bomber apply to many civil and military transport aircraft. Curves for aircraft with characteristics not similar to those investigated can be constructed by the same methods.

3 Results

The results of the calculations are plotted in Figs.1 - 8, and are discussed below.

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* "Standard" aircraft are defined as those with characteristics similar to fighters and bombers coming into production in 1952.

The lighter form of wing construction, spar or box-beam, is assumed in each case. The change from spar to box-beam construction is marked on Figs.1 - 4 and is characterised by an abrupt reduction in slope of the curves. The abrupt increases in slope occur when the weight of cover required for torsional stiffness first exceeds that required for local strength and stiffness under airloads, and when the weight of shear webs required for torsional stiffness first exceeds that for vertical shear strength.

4 Design Speed (V_D) and Normal Acceleration (N)

Figs.1A and 3A give the structure weights of the standard fighter and bomber respectively, for ranges of V_D and N . The curves for total structure weight show these features:-

(a) structure weight increases with both V_D and N ,

(b) the slope of the curves, which gives the rate of change of structure weight with V_D , increases as V_D increases, but is not greatly affected by the value of N .

(c) the spacing of the curves, which gives the rate of change of structure weight with N , is the same for all values of V_D and N when spar construction is used, but is reduced with increase of V_D when box-beam construction is used.

At average values of V_D (600 knots for the fighter, 400 knots for the bomber) a change in structure weight of 1% of the aircraft weight corresponds to a change of about:-

(i) 35 knots in V_D , or 1.5 in N for the standard fighter,

(ii) 35 knots in V_D , or 0.8 in N for the standard bomber.

5 Wing Loading and Geometry

Figs.1B, C and D, and 3B, C and D give curves similar to those of Figs.1A and 3A respectively, but with values of wing aspect ratio, thickness/chord ratio and taper ratio other than the standard values.

Figs.2A and C, and 4A and C give similar curves for other values of wing loading. Figs.1A and 3A are reproduced as Figs.2B and 4B for convenience.

These curves all show the general features noted in paragraph 4 for the standard aircraft, but the actual weights of the wing and total structure are greatly affected by wing loading and geometry. This is illustrated by Table II, which gives changes in structure weight, expressed as a percentage of the aircraft weight, for given changes in V_D and N under various conditions. The changes in structure weight increase rapidly for increased aspect ratio, and for reduced wing loading and thickness/chord ratio.

Table II also illustrates the increasing importance of V_D , relative to that of N , as V_D is increased.

6 Sweepback

In the method used for calculating wing weight, the weight of cover material required for torsional stiffness, which depends on V_D , is independent of sweep, so that variations of structure weight with V_D are not affected.

The weight of bending material, which depends on N , does vary, and Fig.5 shows how the wing, tail unit and total structure weight vary with sweepback for the standard fighter. These curves should be regarded as approximate because the method does not allow for the high flexural stiffness which may be necessary for adequate stability and control for some wings of high sweep and aspect ratio.

7 Type of Construction

At low values of V_D the wing cover is thin, and the lightest way to provide bending strength is to use concentrated spar flanges. As V_D is increased the cover weight rapidly becomes greater, because the required torsional stiffness increases with V_D^2 , and above some "critical" value of V_D it is lighter to reinforce the cover to provide the bending strength (i.e. to use box-beam construction). The critical value of V_D is reduced as N , wing loading and thickness/chord ratio are reduced. Fig.6 shows the full spar and box-beam curves for three values of thickness/chord ratio. The critical value of V_D is lower for the bomber than for the fighter, because there is a larger proportion of relief loads in the bomber wing, and because, as size increases, the weight of material required for torsion increases more rapidly than that required for bending.

These facts explain several features noted in paragraph 4. For spar construction the bending material, affected by N , and the torsion material, affected by V_D^2 , are separate. The curves have the same slope, which increases as V_D is increased, and the same spacing. For box-beam construction bending and torsion material are common. Usually the outer part of the semi-span is designed by torsional requirements, and the inner part by bending. The outer part has a reserve of strength in bending and a given change in N involves less change in structure weight than for spar construction. The curves thus tend to converge above the critical value of V_D .

8 Aircraft Size

The total structure weight, expressed as a percentage of the aircraft weight, varies as the aircraft size is varied. The relative weights of the various structural components also change. Care is therefore necessary in applying the results of this report to aircraft of sizes different from those examined.

The structure weights of a family of fighters and a family of bombers are calculated as a guide and shown on Figs.7 and 8 respectively. These aircraft have varying wing area but "standard" characteristics in other respects, i.e. the same V_D , N , w , A , t/c , λ, and the same proportion of relief loads, fuselage and tail areas, etc.

The curves suggest that the total structure weight of similar aircraft varies with $(\text{aircraft weight})^{1.20}$, instead of $(\text{aircraft weight})^{1.50}$ as suggested by the theoretical "square-cube" law, whereby aircraft weight varies with the square, and the structure weight with the cube of the linear dimension.

9 Conclusions

(1) A change in structure weight of 1% of aircraft weight corresponds to change of about:-

(i) 35 knots in V_D , or 1.5 in N for the "standard" fighter,

(ii) 35 knots in V_D , or 0.8 in N for the "standard" bomber.

(2) These values are greatly affected by variations in wing loading and geometry, and by the value of V_D at which the changes are made.

(3) The importance of V_D, relative to that of N, increases as V_D is increased.

(4) Spar type wing construction is lighter than box-beam for low values of V_D. Above some value, which depends upon wing loading and geometry, and aircraft size, box-beam construction is the lighter.

(5) The structure weight of similar aircraft is calculated to vary with $(\text{aircraft weight})^{1.20}$, instead of $(\text{aircraft weight})^{1.50}$ as suggested by the theoretical "square-cube" law.

REFERENCES

No.	Author	Title, etc.
1	E.L. Ripley	A method of wing weight prediction. A.R.C. 14,269. May, 1951.
2	M.E. Burt and J. Phillips	Prediction of fuselage and hull structure weights. A.R.C. 15,121. March, 1952.
3	E.L. Ripley	A simple method for tail unit structure weight prediction. A.R.C. 13,710. Strut.1406. November, 1950.

APPENDIX I

Details of Structure Weight Calculations

1 Wing Weight

1.1 The method used is substantially due to Ripley[1], but with some simplifications in the treatment of relief loads and weight allowances for special features. It is described as briefly as possible except for the departures from the full method.

The wing structure weight is given by

$$W_W = k\,W_{WB}$$

where W_{WB} = weight of basic wing structure

$= W_C + W_B + W_S + W_{IS}$

W_C = weight of cover material

W_B = weight of bending material

W_S = weight of shear material

W_{IS} = weight of internal structure

$k-1 = \dfrac{\text{weight of special features}}{\text{weight of basic wing structure}}$

The use of the factor k is the first simplification of the full method. The weight of the special features is calculated by multiplying the weight of the basic wing by a factor based upon experience of wings similar to that under investigation, not by individual assessment.

1.2 The weight of cover material for both spar and box-beam constructions is given by

$$W_C = W_{TC} + W_{RC}$$

where W_{TC} = weight of torsion box cover

W_{RC} = weight of remainder of cover

The uniform wt/sq.ft (C_T) of the torsion box cover is given by Equation 3.15*, provided that $C_T \nless C_R$ as given by the "smooth finish" curve of Fig.25. The uniform wts/sq.ft (C_R) of the leading edge and trailing edge are obtained from Fig.25, using the "smooth finish" curve for the leading edge.

The torsion box is assumed continuous across the fuselage, but the leading and trailing edges are removed.

---

* All references in this Appendix to Equations, Paragraphs and Figures are to those of Ref.1.

1.3 The weight of bending material (W_B) for spar type construction is obtained from Equations 2.15, 2.22 and a simplified form of 2.21, which is

$$K_5 = N (W - W_R) \frac{I_3}{I_1} I_9$$

where W_R = weight of wing group (i.e. structure, engines fuel,etc.).

This is the second simplification. It is assumed that the spanwise weight distribution of the items which relieve the airloads on the wing is the same as that of the airloads. Account of the relief loads is then taken by subtracting their total weight (W_R) from the aircraft weight in the equation for K_5.

The "two spar" curve of Fig.24 is used.

For box-beam type construction the spanwise distribution of the material required for bending and the torsion material effective in bending are plotted as in Sketch 4.3. The weight of bending material (W_B) is the additional material required for bending and shown hatched on Sketch 4.3. The spanwise distribution of the net material required for bending is given by a modification of Equation 2.09.

$$B_B = K_7 N (W - W_R) \frac{I_2}{I_1} I_9 I_4 J_4$$

The spanwise distribution of the torsion material effective in bending is obtained by assuming that three-quarters of the total torsion box cover is effective in bending.

1.4 The weight of material (W_S) required for vertical shear strength is calculated from Equations 5.10, 5.15 and 5.13 modified. The modification to Equation 5.13 is to introduce the same assumption on distribution of relief loads which was made for the bending material. The equation becomes

$$K_2 = \frac{6.2}{10^5} b N \sec \Lambda (W - W_R) I_6$$

This value of W_S is used unless over-ridden by that required in the webs for torsional shear stiffness. This is given by

$$W_S = (p + q) d_o \frac{1 + B\lambda}{2} b \sec \Lambda C_T$$

where p and q are the ratios of the depth of the aerofoil section at the front and rear web positions to the maximum depth.

1.5 The weight of internal structure (W_{IS}) is calculated as given in paragraph 3.7.

2 Fuselage Weight

2.1 The method used is a simplification of the method given by Burt and Phillips[2]. Examination of the components of the fuselage structure of a number of fighters and bombers shows that, for the purpose of this report, fuselage structure weight may be expressed as

$$W_F = a\,W_G + b\,W$$

where W_G = gross fuselage shell weight, calculated as in Ref.2 and a, b are constants obtained from examination of existing aeroplanes. Their values are given in Table I.

3 Tail Unit Weight

3.1 The tail unit structure weight is calculated by Ripley's method[3]. Allowance is made for sweepback and 15% added to the total for mass-balance weights.

4 Undercarriage Weight

4.1 The undercarriage weight is assumed to be 0.05W in all cases.

TABLE I

CHARACTERISTICS OF AIRCRAFT INVESTIGATED

Item	Symbol	Fighter Aircraft		Bomber Aircraft	
		Standard Value	Other Values Considered	Standard Value	Other Values Considered
Wing Area sq.ft.	S	300	100, 200 500, 700	2,000	500, 1000 3000, 4000
Wing Loading lb/sq.ft.	w	50	25, 100	50	25, 100
Aircraft Weight lb	W	15,000		100,000	
Design Diving Speed knots E.A.S.	V_D	600	400, 500 700, 800	400	200, 300 500, 600
Factored Maximum Normal Acceleration Coefficient at Weight W (Manoeuvre or gust)	N	12.0	6.0, 9.0	4.5	3.0 6.0, 7.5
Aspect Ratio	A	4	2, 6	5	3, 7
Thickness/Chord Ratio	t/c	10%	5%, 15%	10%	5%, 15%
Taper Ratio	λ	0.5	0.25, 0.75	0.5	0.25, 0.75
Sweepback (on 0.25 chord line)	Λ	40°	0°, 20°, 60°	25°	
Torsion Box Forward and Aft Limits		0.2 c 0.6 c		0.2 c 0.6 c	
$\frac{\text{Effective Bending Depth}}{\text{Maximum Local Wing Depth}}$) Spars) Box-Beam	γ	0.85 0.94		0.85 0.94	
$\frac{\text{Weight of Wing Group}}{\text{Aeroplane Weight}}$	$\frac{W_R}{W}$	0.2		0.4	
$\frac{\text{Weight of Special Features}}{\text{Basic Wing Weight}}$	k - 1	0.40		0.35	
$\frac{\text{Fuselage Area}}{\text{Wing Area}}$		1.60		1.25	
Fuselage Fineness Ratio	$\frac{L_T}{B + H}$	2.2		2.5	
Constants in Fuselage Weight Equation, Appendix I	a b	1.50 0.02		1.55 0.02	
Fuselage Width at Wing Level ft.		4.0		10.0	
$\frac{\text{Tailplane and Elevator Area}}{\text{Wing Area}}$		0.16		0.16	
$\frac{\text{Fin and Rudder Area}}{\text{Wing Area}}$		0.08		0.08	

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TABLE II

Changes in Structure Weight (Percentage of Aircraft Weight) for Changes in Design Diving Speed (V_D) and Factored Normal Acceleration Coefficient (N)

FIGHTER AIRCRAFT		Changes in V_D at N = 12		Change in N from 9 to 12		BOMBER AIRCRAFT		Changes in V_D at N = 4.5		Change in N from 3 to 4.5	
		400 to 500 kts	700 to 800 kts	At V_D = 400 kts	At V_D = 800 kts			200 to 300 kts	500 to 600 kts	At V_D = 200 kts	At V_D = 600 kts
Standard		1.4	2.8	2.0	2.1	Standard		1.7	4.6	1.9	1.3
Aspect Ratio	2	1.3	1.9	1.1	1.2	Aspect Ratio	3	1.6	2.6	1.3	1.0
	6	2.5	4.2	3.0	3.2		7	3.4	6.7	2.7	1.4
Thickness/Chord Ratio	5%	4.0	4.9	3.1	2.7	Thickness/Chord Ratio	5%	4.3	14.3	3.1	0.4
	15%	1.3	2.0	1.7	1.7		15%	1.6	2.6	1.6	1.4
Taper Ratio	0.25	1.3	2.7	1.6	1.6	Taper Ratio	0.25	1.6	4.7	1.8	0.6
	0.75	1.7	3.2	2.9	2.3		0.75	1.9	5.0	2.1	1.6
Wing Loading	25	2.6	5.9	2.1	1.8	Wing Loading	25	3.4	10.9	2.1	0.8
	100	0.7	1.4	1.9	1.9		100	0.8	1.7	1.8	1.4

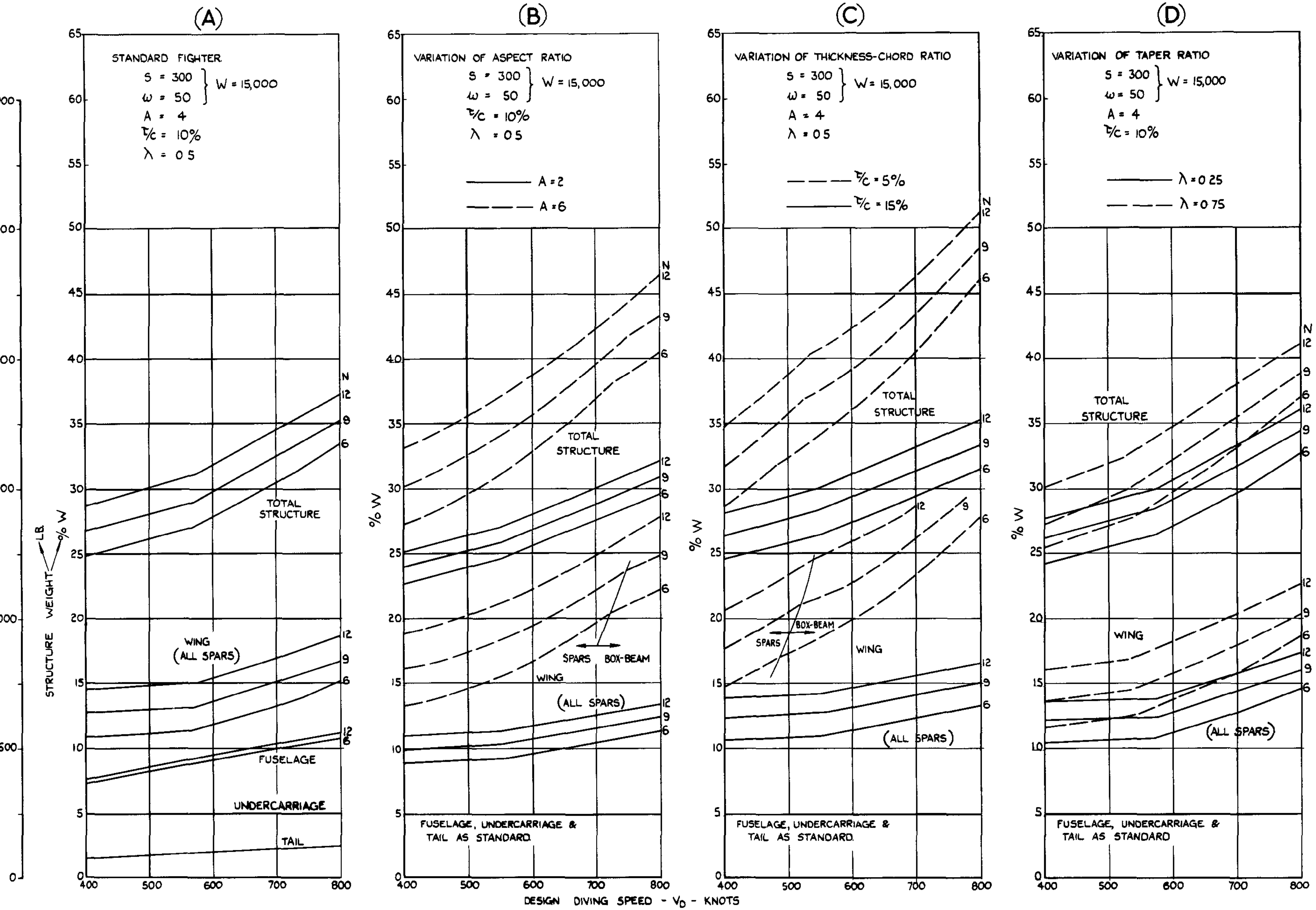

FIG. 1 (A-D) FIGHTER AIRCRAFT — VARIATION OF STRUCTURE WEIGHT WITH V_D & N, FOR VALUES OF A, $\frac{t}{c}$ & λ.

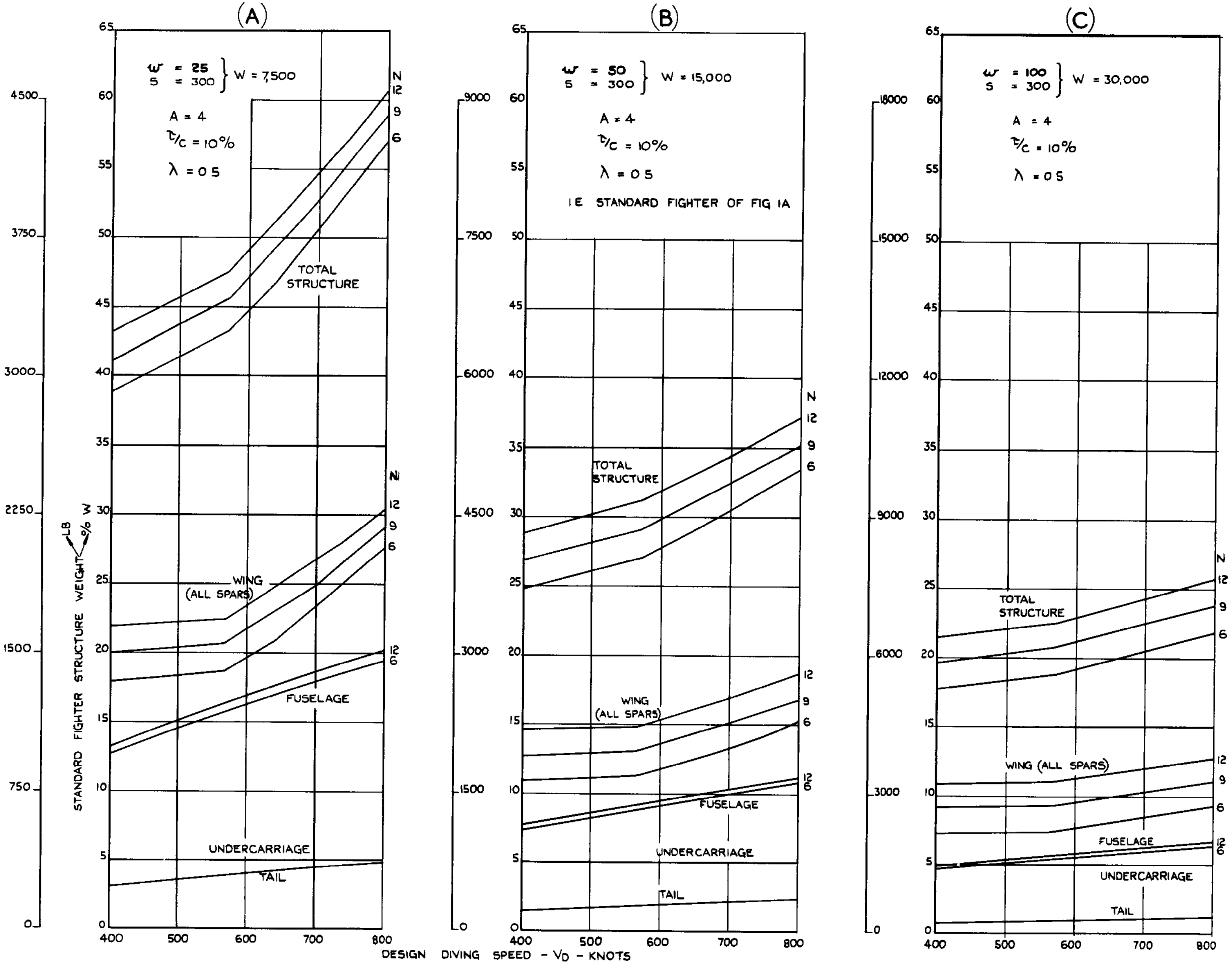

FIG.2(A-C) FIGHTER AIRCRAFT – VARIATION OF STRUCTURE WEIGHT WITH V_D & N, FOR VALUES OF WING LOADING (ω).

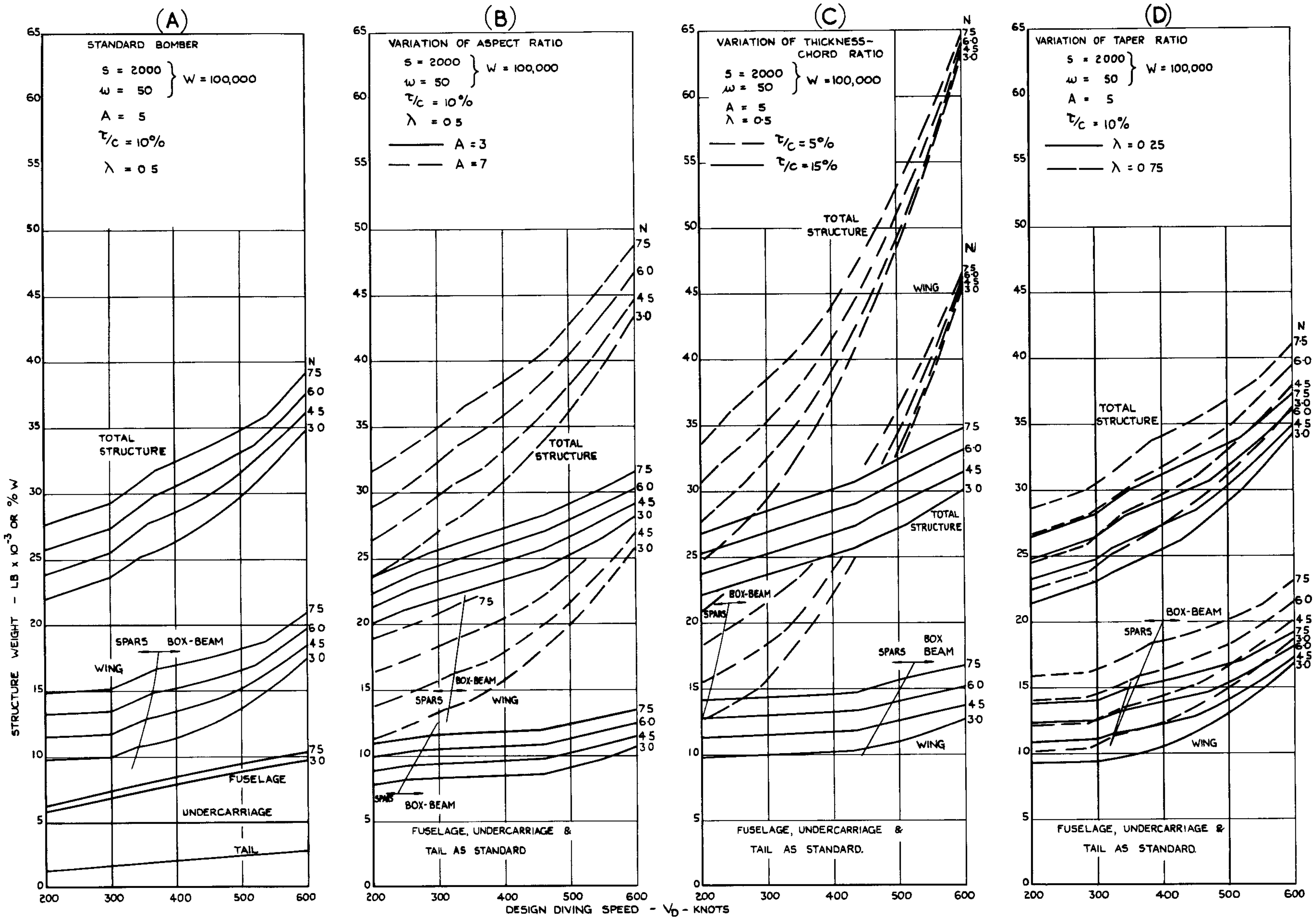

FIG.3(A-D) BOMBER AIRCRAFT–VARIATION OF STRUCTURE WEIGHT WITH V_D & N, FOR VALUES OF A, τ/c & λ.

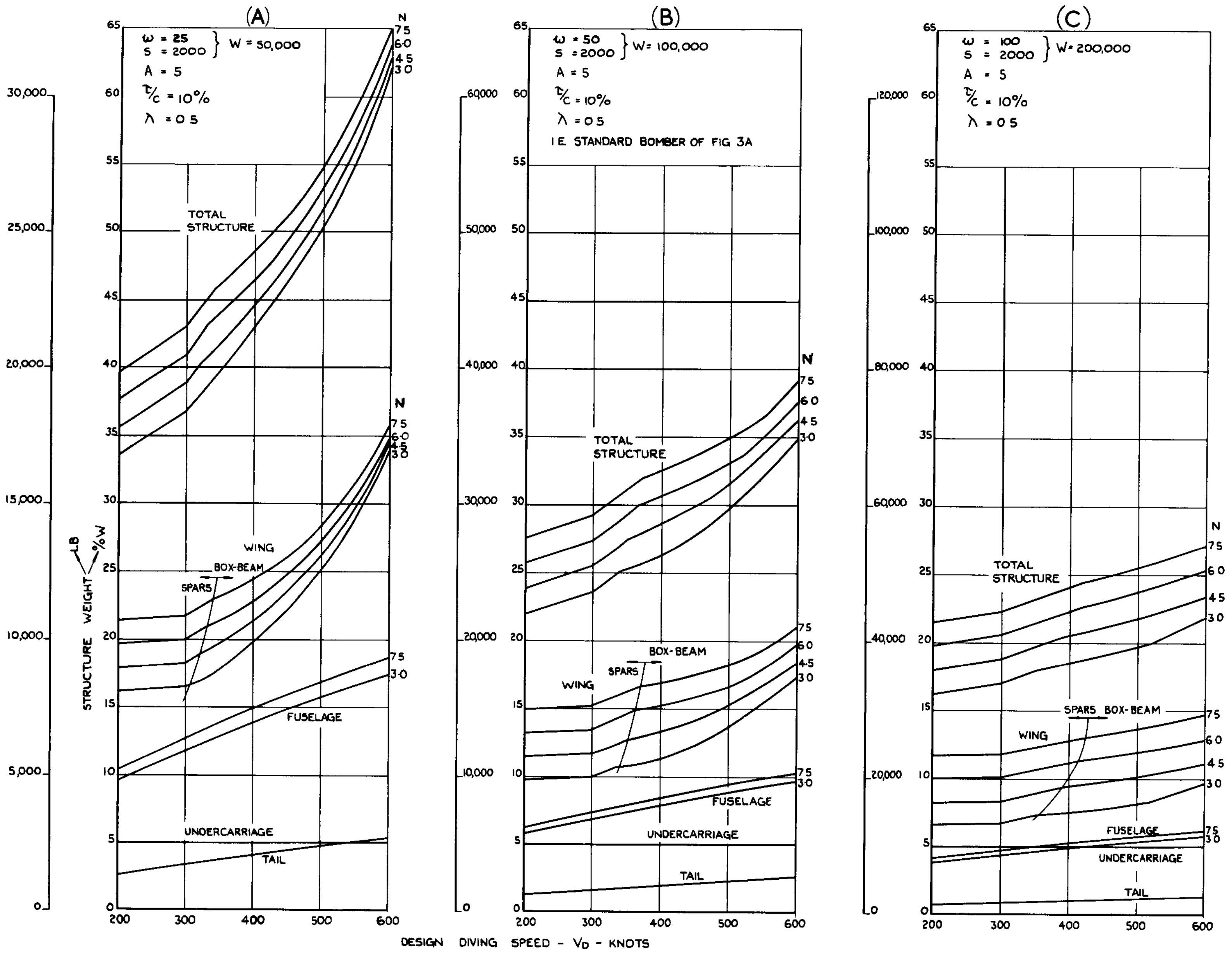

FIG.4(A-C) BOMBER AIRCRAFT-VARIATION OF STRUCTURE WEIGHT WITH V_D & N, FOR VALUES OF WING LOADING (ω).

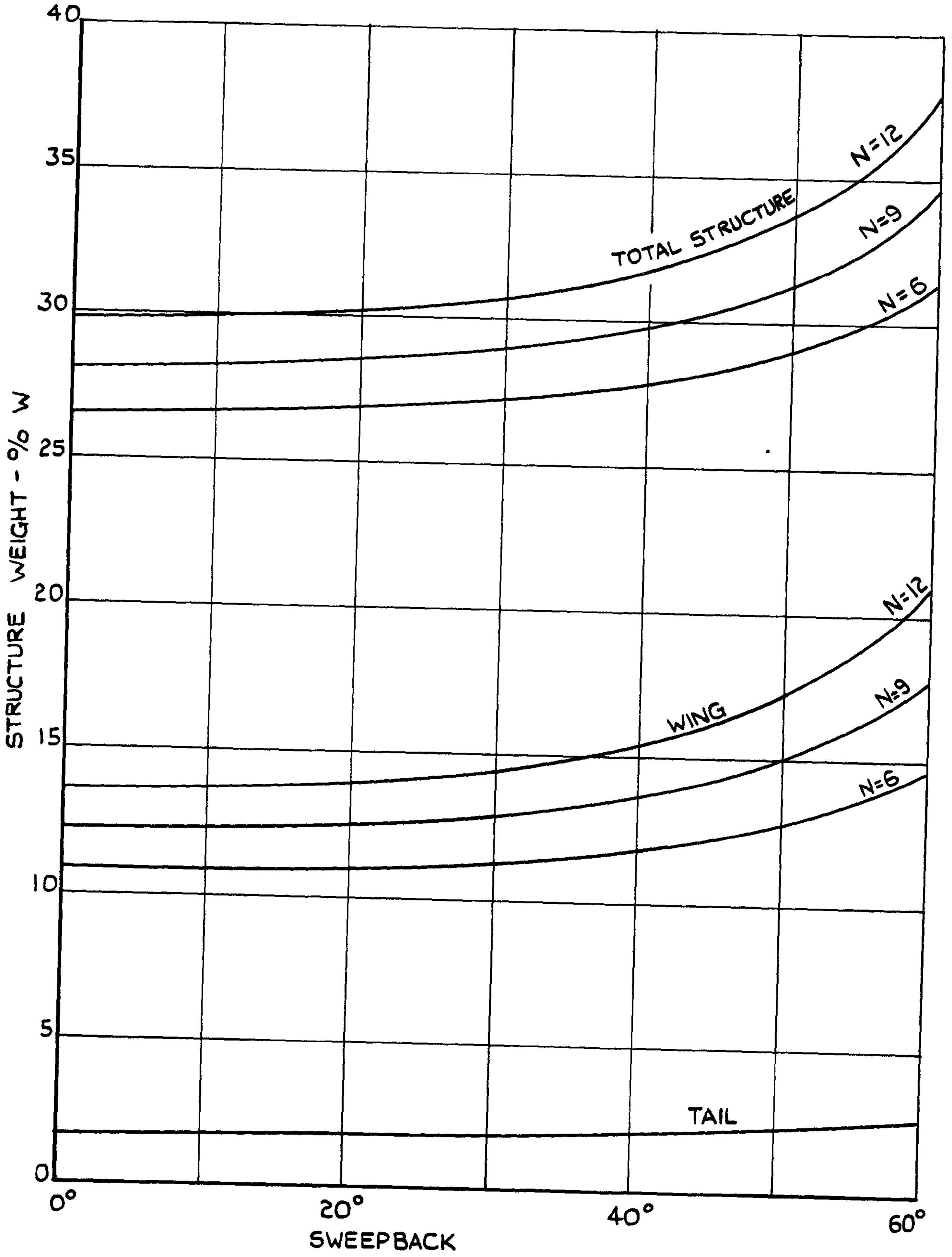

FIG.5. VARIATION OF STRUCTURE WEIGHT WITH SWEEPBACK FOR STANDARD FIGHTER.

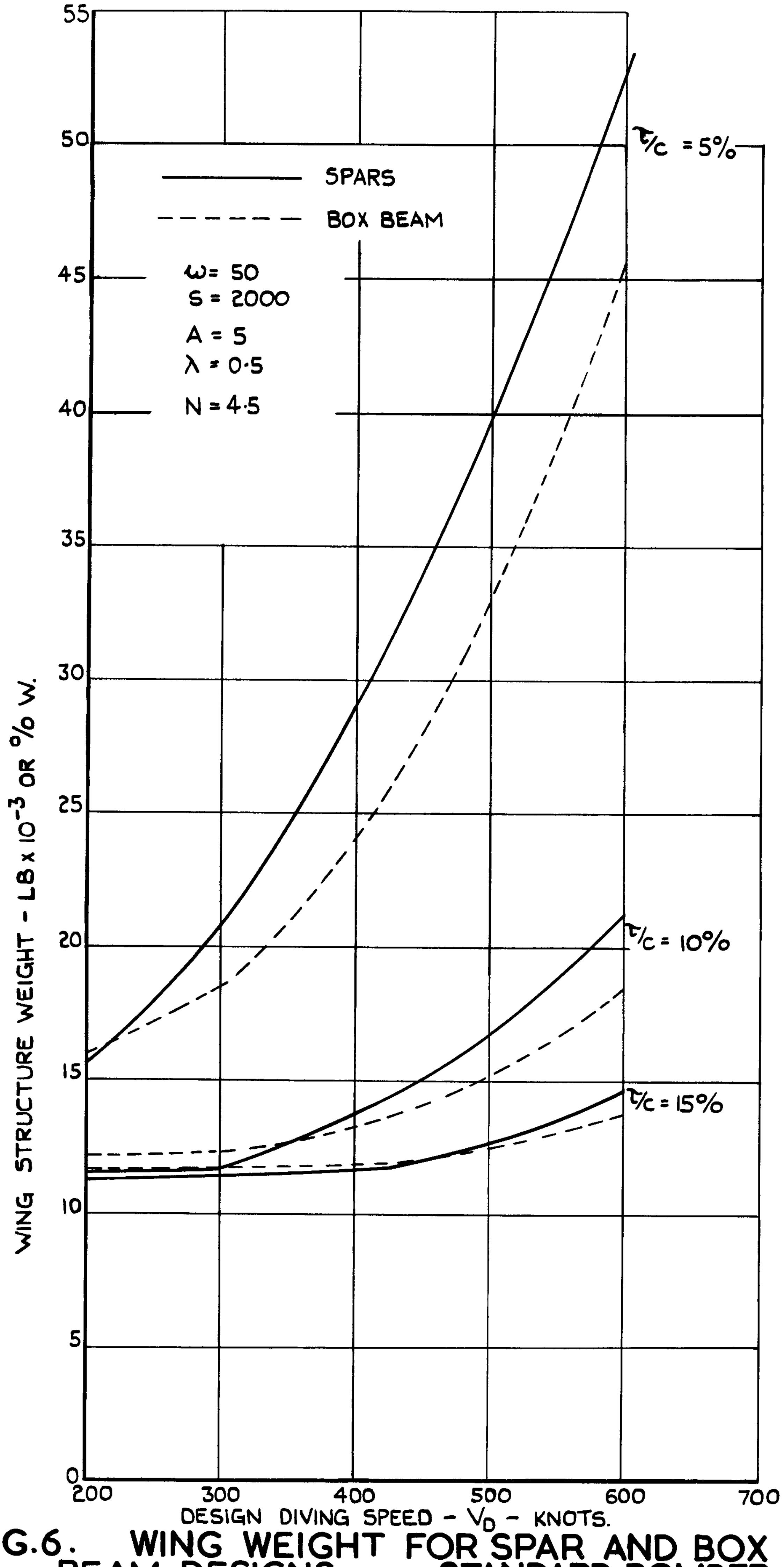

FIG.6. WING WEIGHT FOR SPAR AND BOX BEAM DESIGNS. STANDARD BOMBER.

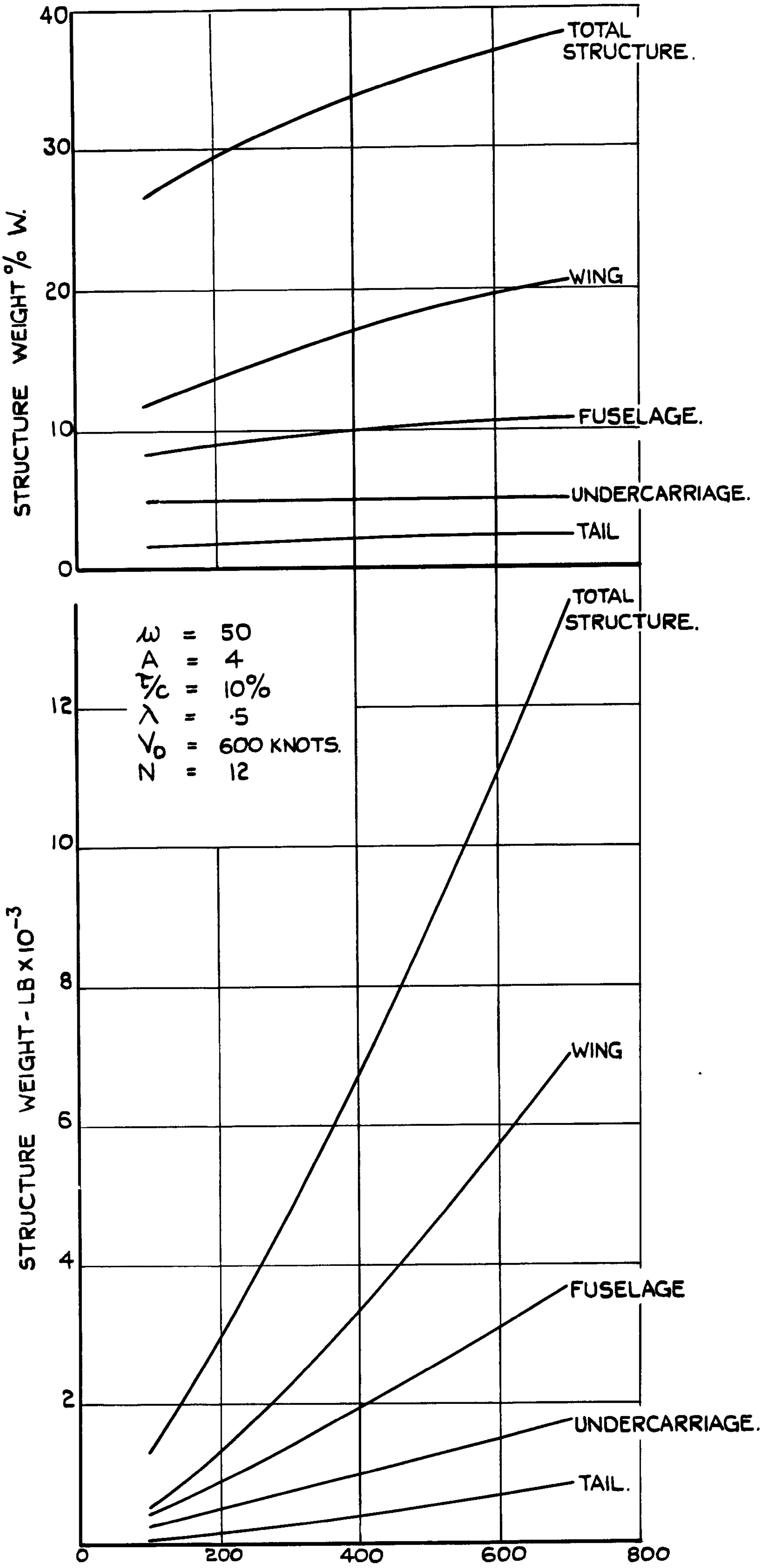

FIG.7. VARIATION OF STRUCTURE WEIGHT WITH AIRCRAFT SIZE FOR SIMILAR FIGHTER AIRCRAFT.

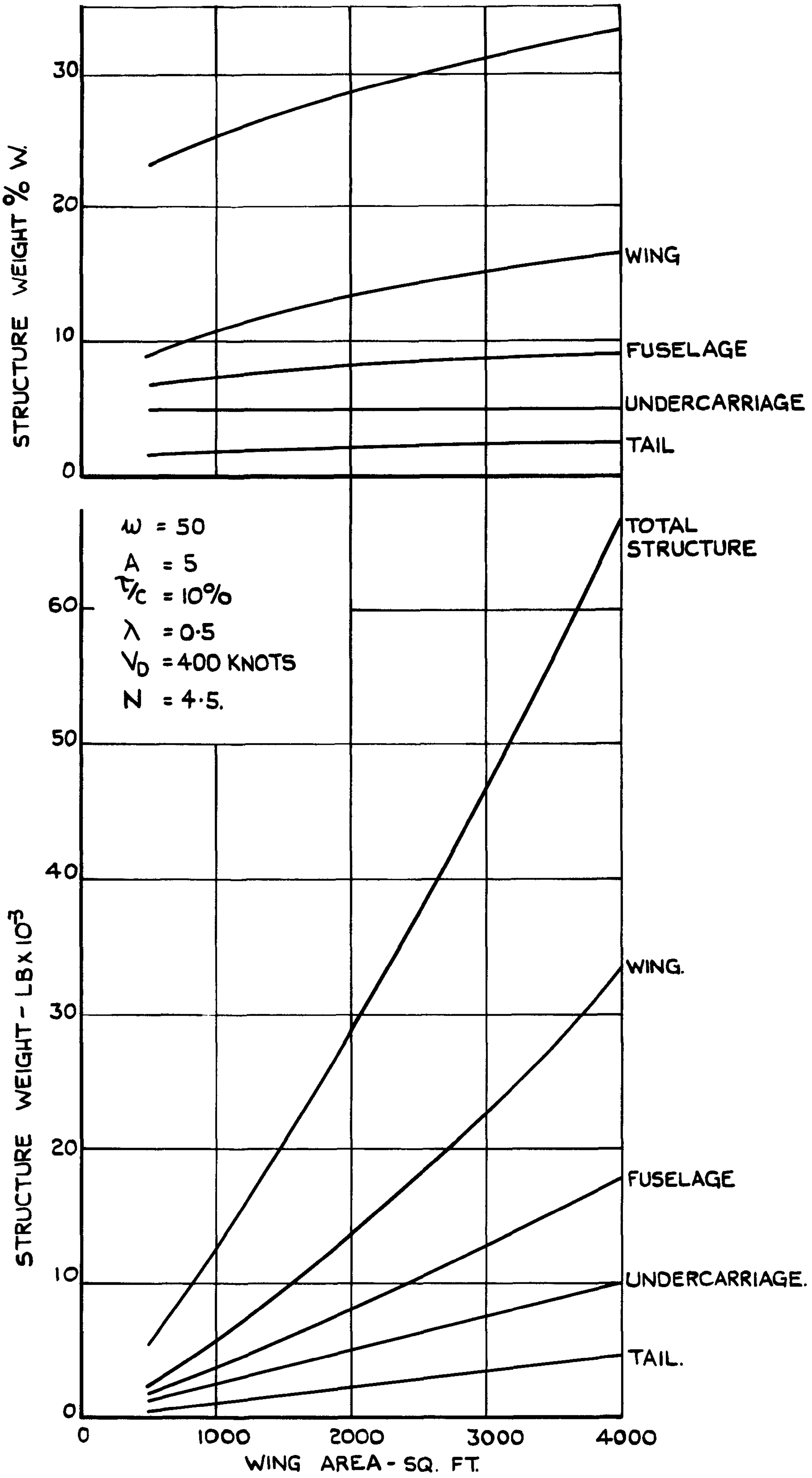

FIG.8. VARIATION OF STRUCTURE WEIGHT WITH AIRCRAFT SIZE FOR SIMILAR BOMBER AIRCRAFT.

FIG. 13

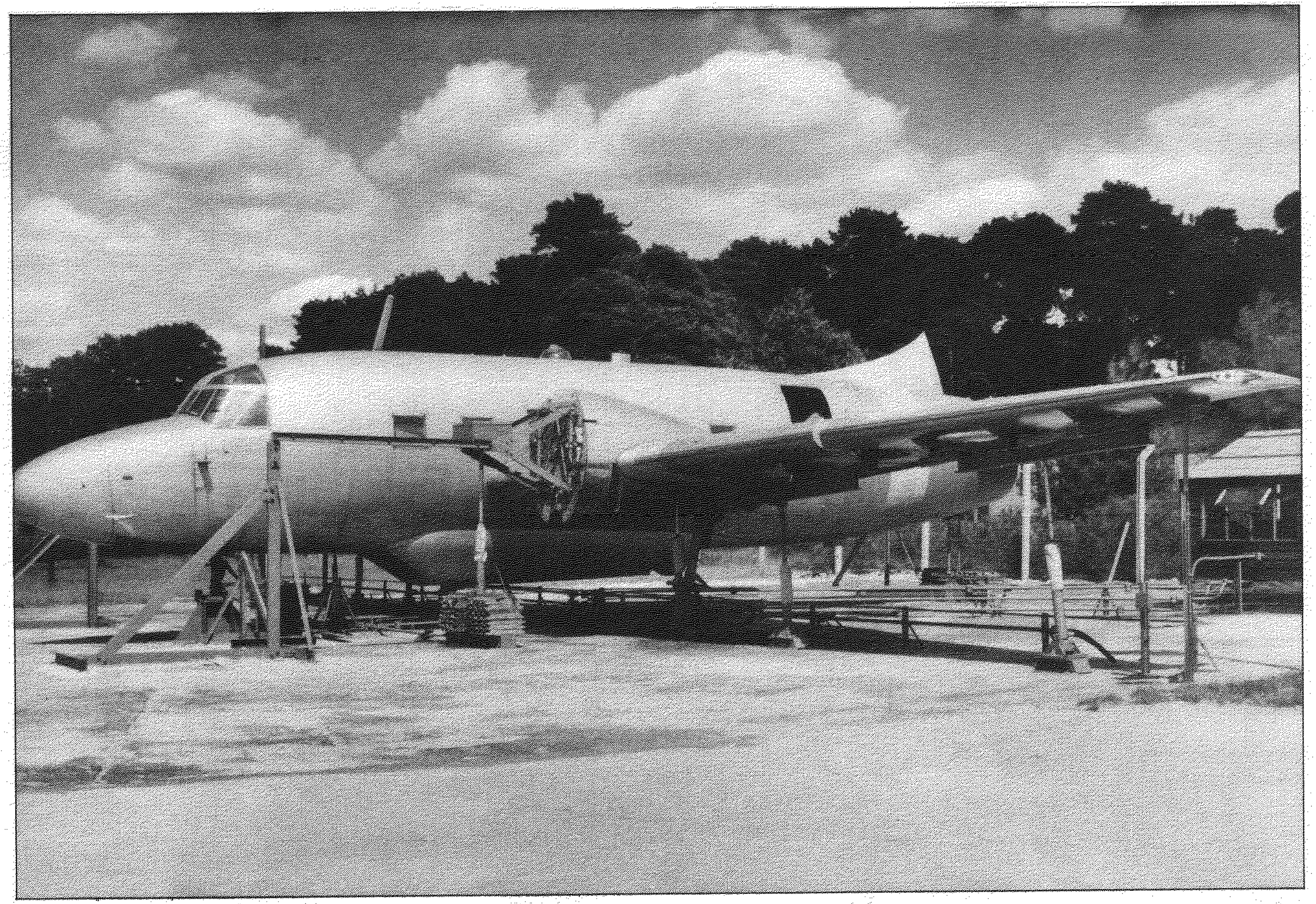

FIG. 14

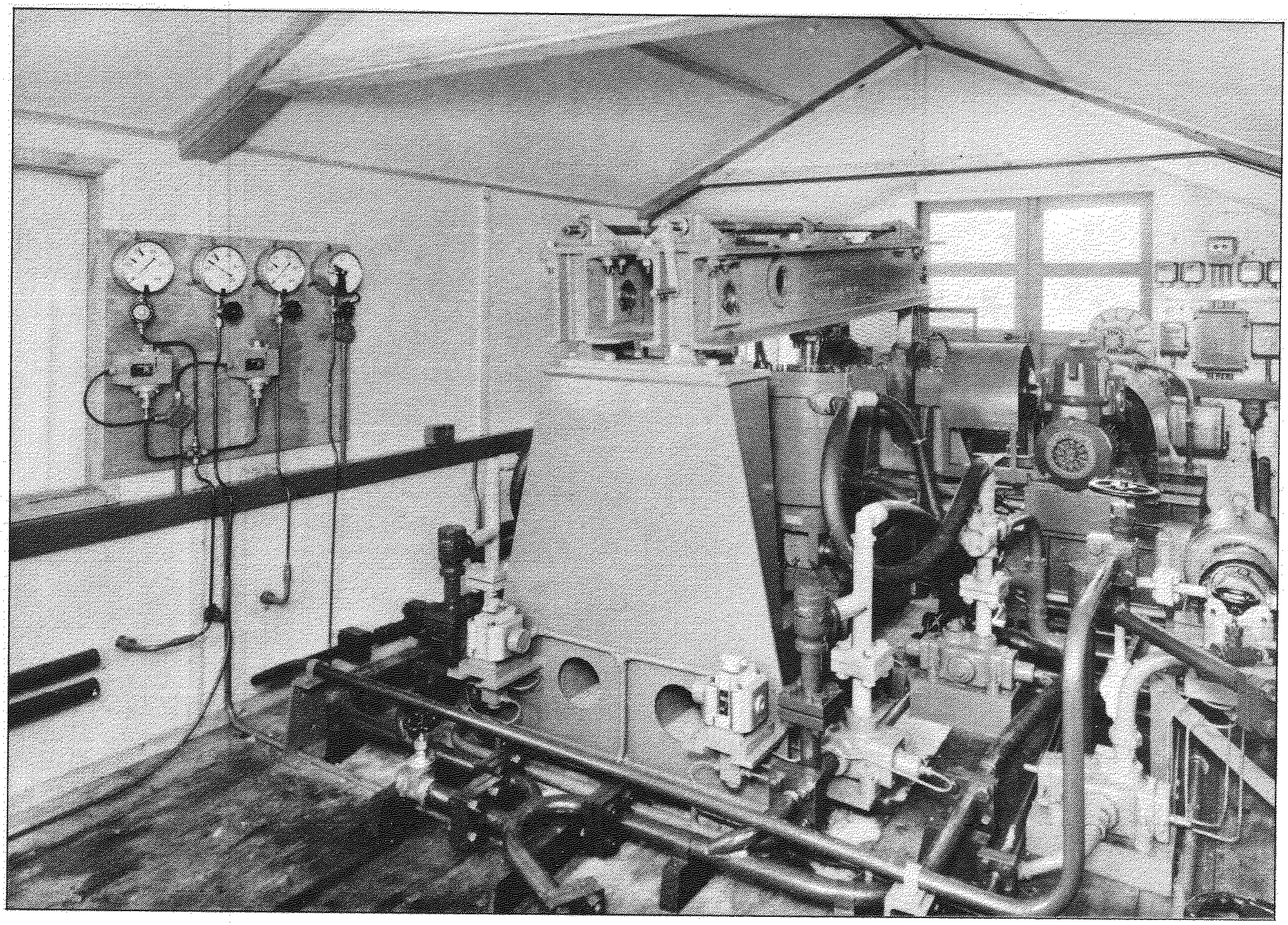

FIG.15

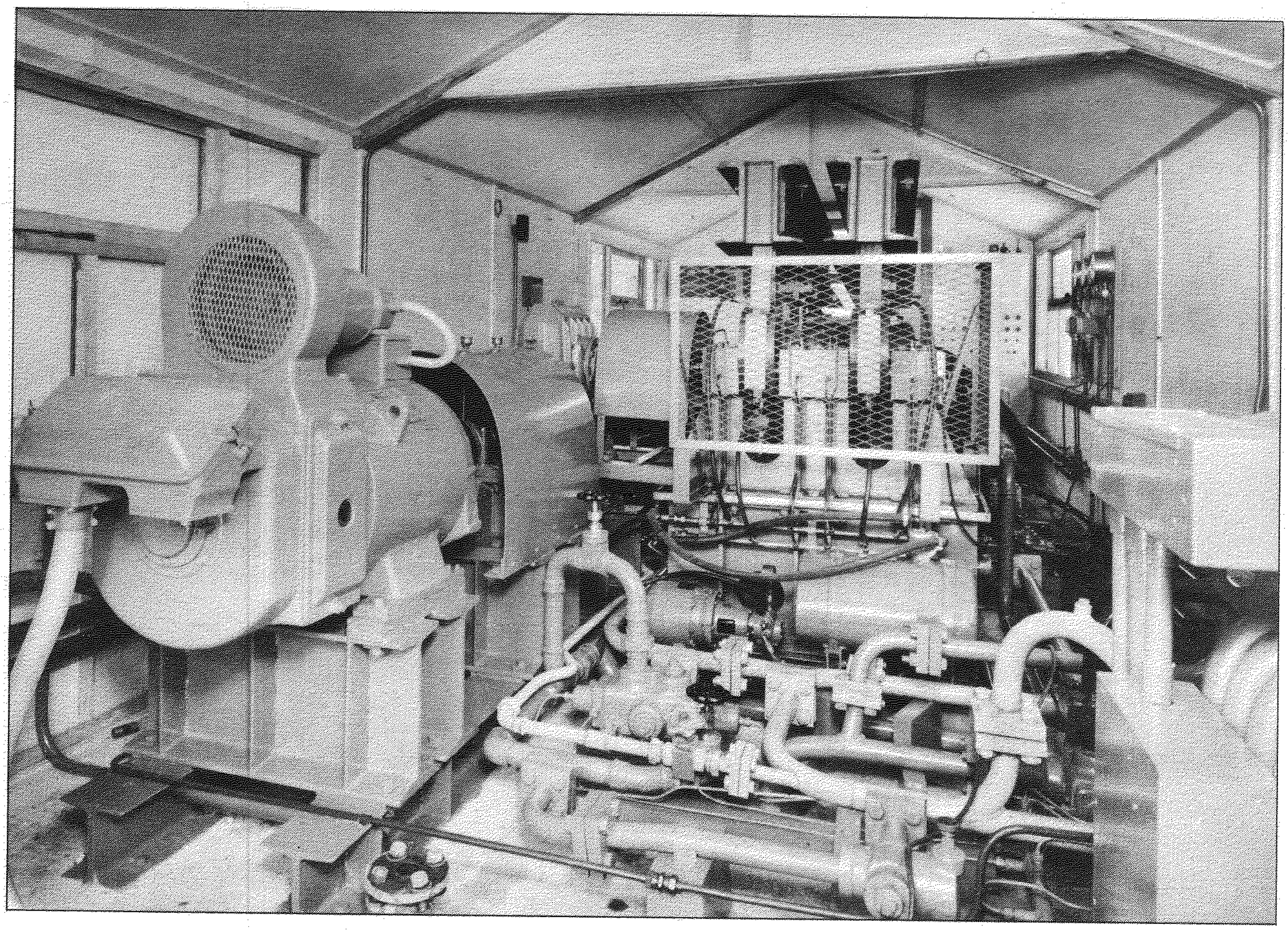

FIG.16

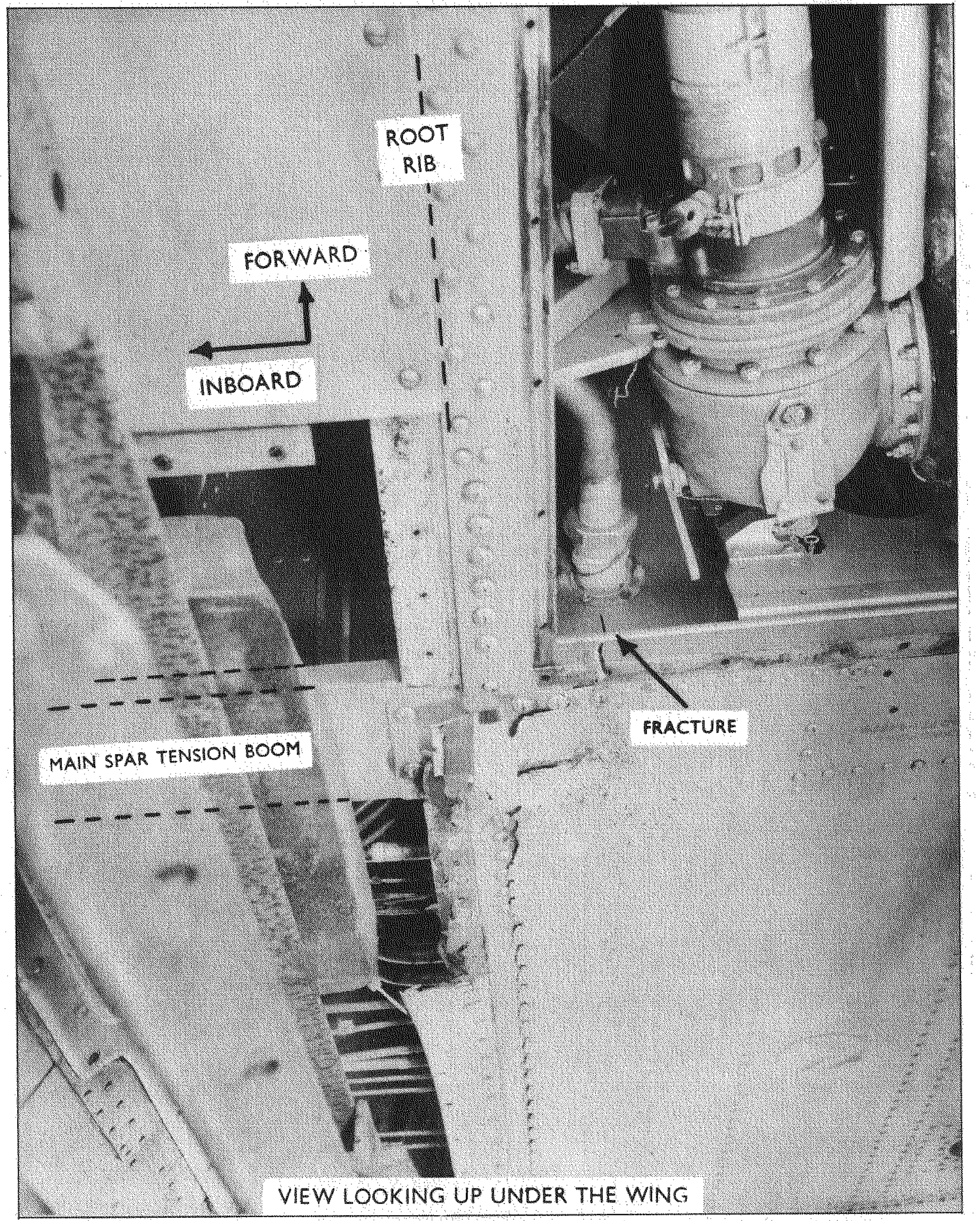

FIG.17. MAIN SPAR TENSION BOOM FRACTURE, PORT INNER WING; 170,500 GUST LOAD CYCLES, FIRST TEST

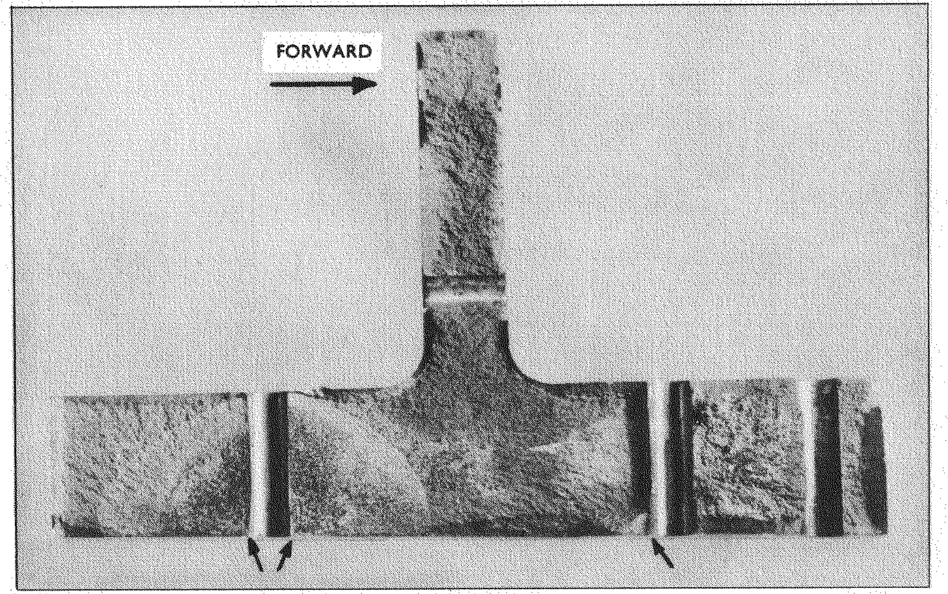

FIG.18. TENSION BOOM FRACTURE, PORT INNER WING, FIRST TEST

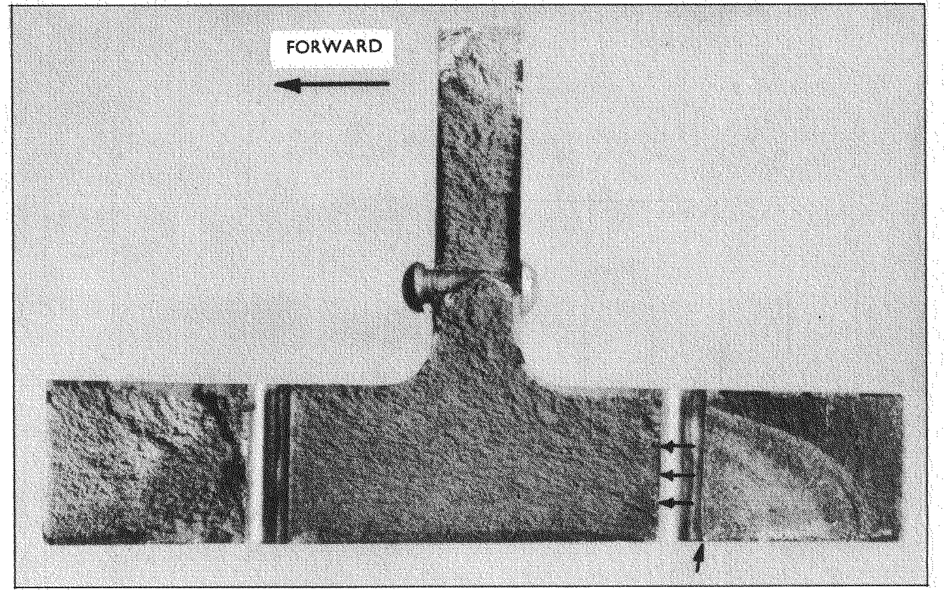

FIG.19. TENSION BOOM FRACTURE, STARBOARD INNER WING, FIRST TEST

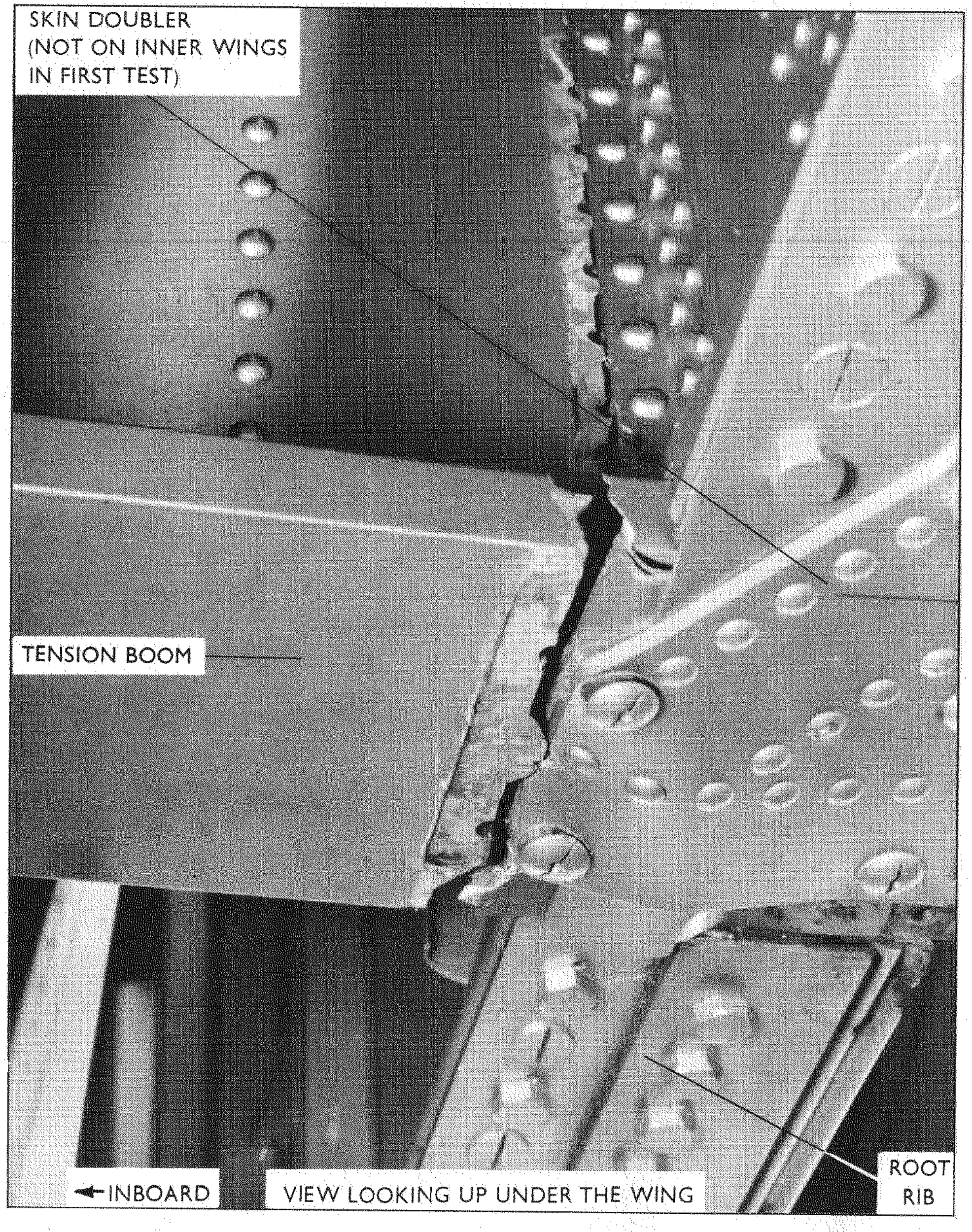

FIG.20. STARBOARD INNER WING; 180,500 LOAD CYCLES, SECOND TEST

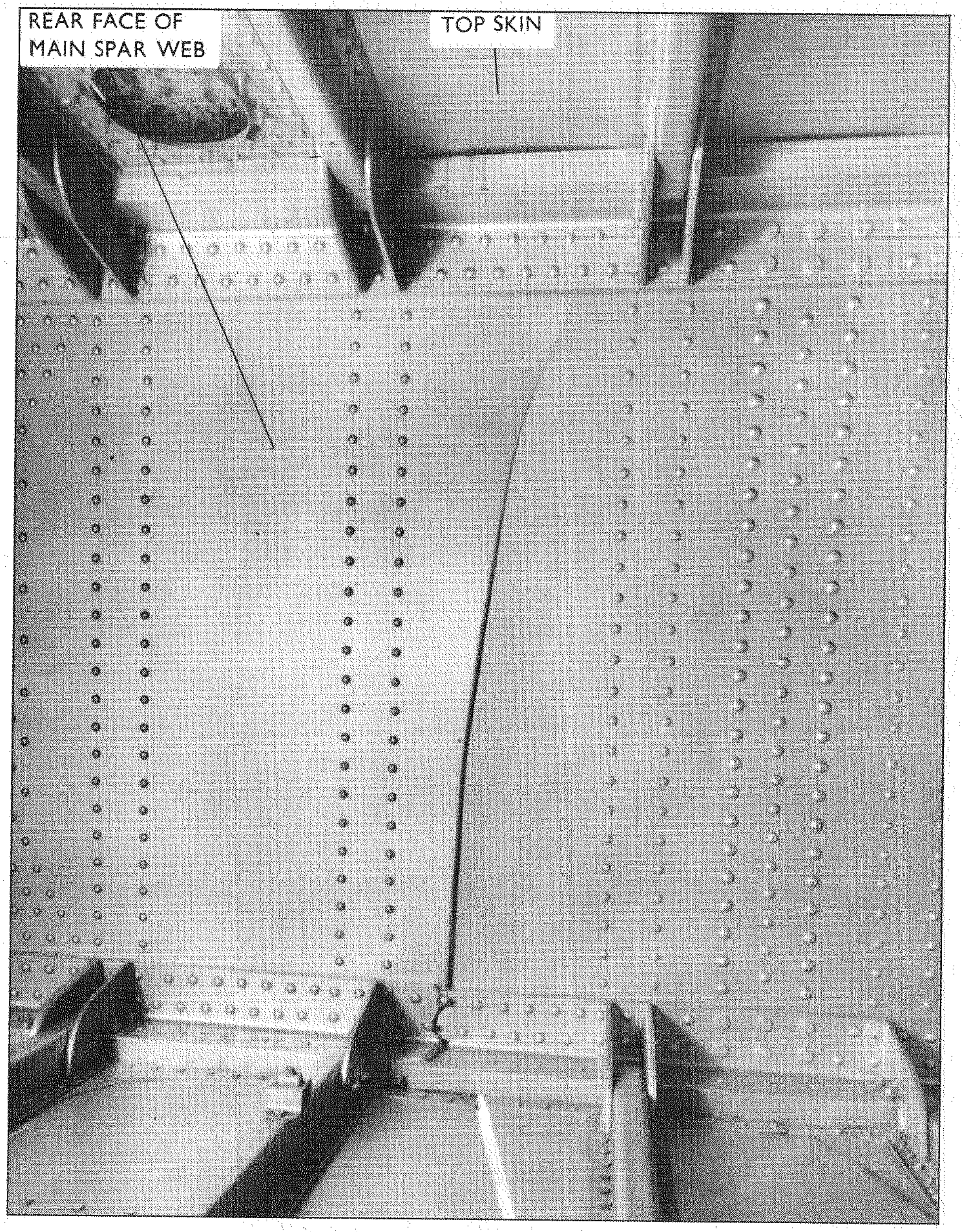

FIG.21. PORT INNER WING; 290,000 LOAD CYCLES, SECOND TEST

FIG.20 & 21. MAIN SPAR TENSION BOOM FRACTURE

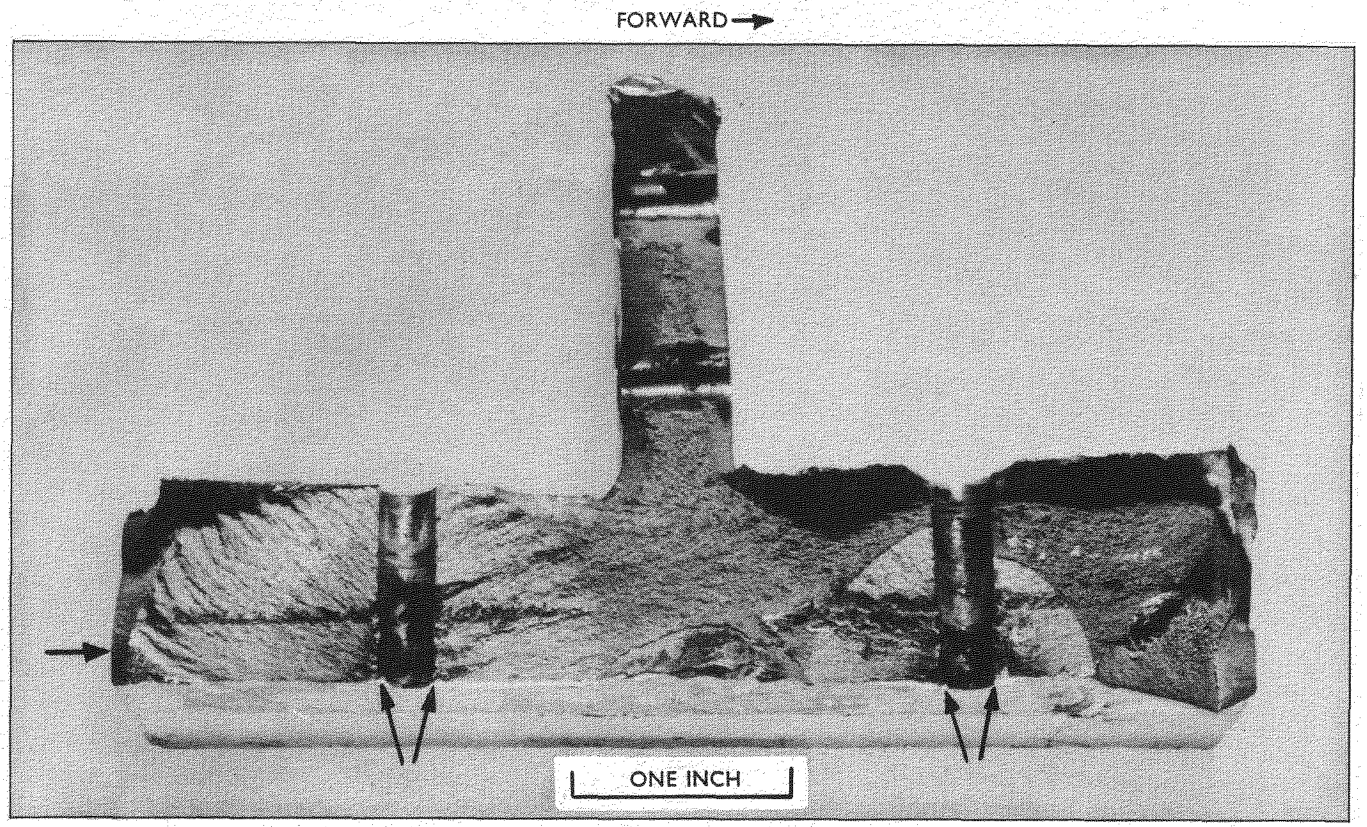

FIG.22. STARBOARD INNER WING, SECOND TEST

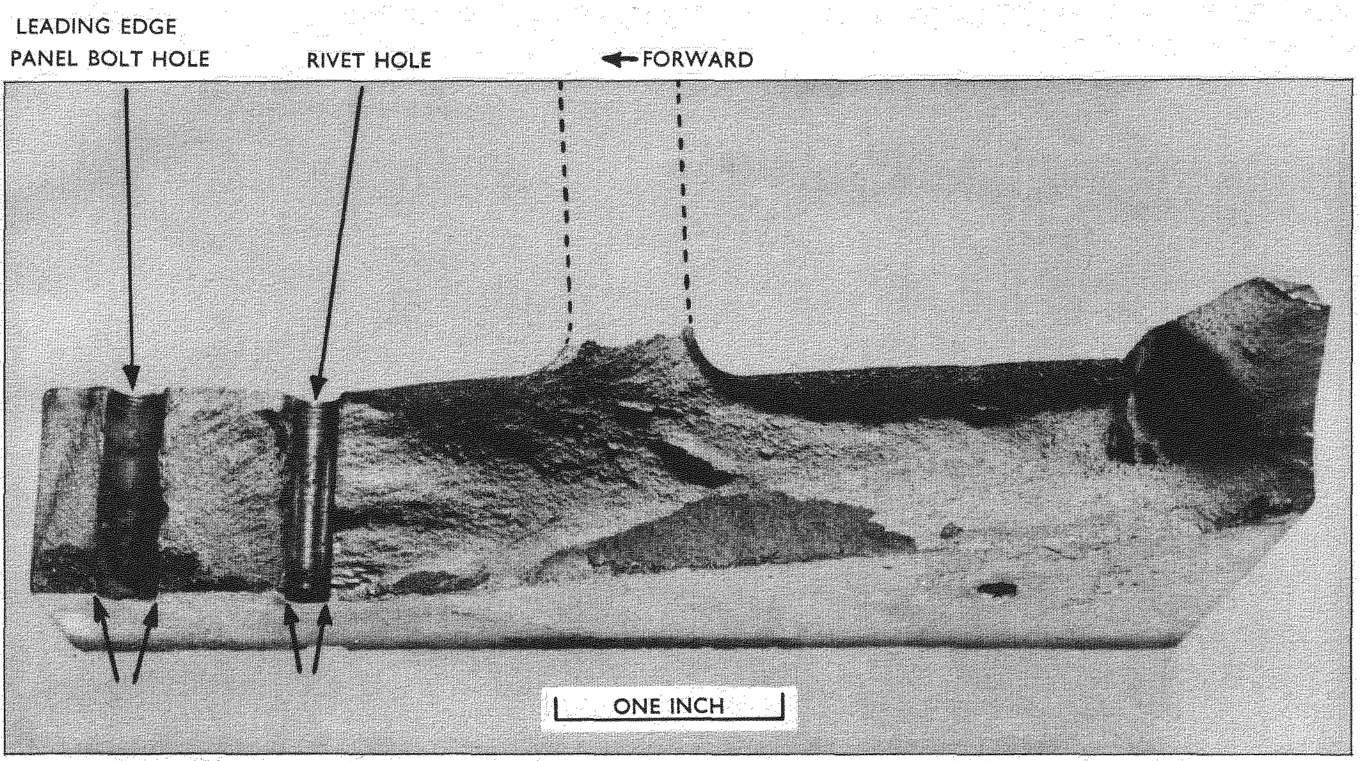

FIG.23. PORT INNER WING, SECOND TEST

FIG.22 & 23. TENSION BOOM FRACTURE

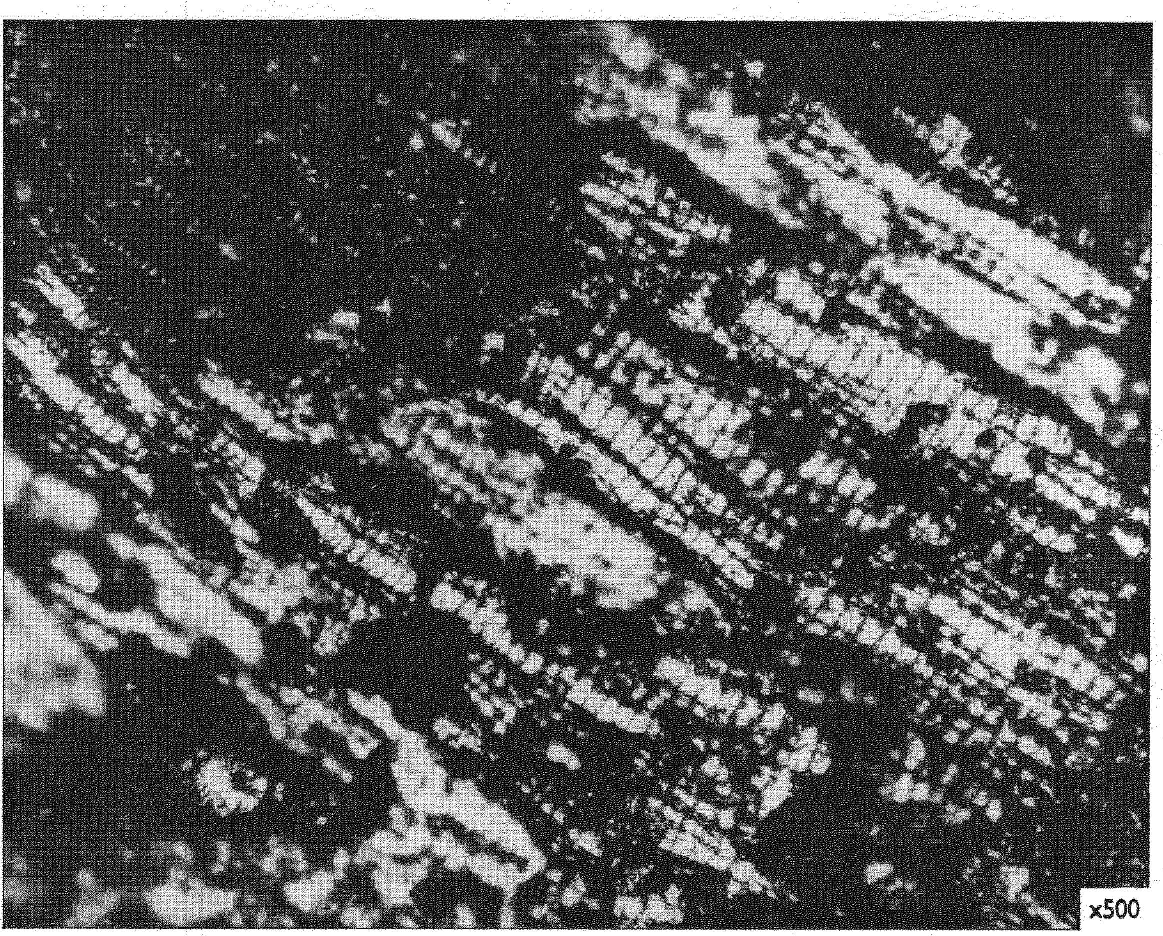

FIG.24. STRIATIONS ON THE FRACTURED SURFACE OF THE B.S.L.65 BOOMS

FIG.25. STRIATIONS FROM INDIVIDUAL GUST LOAD CYCLES

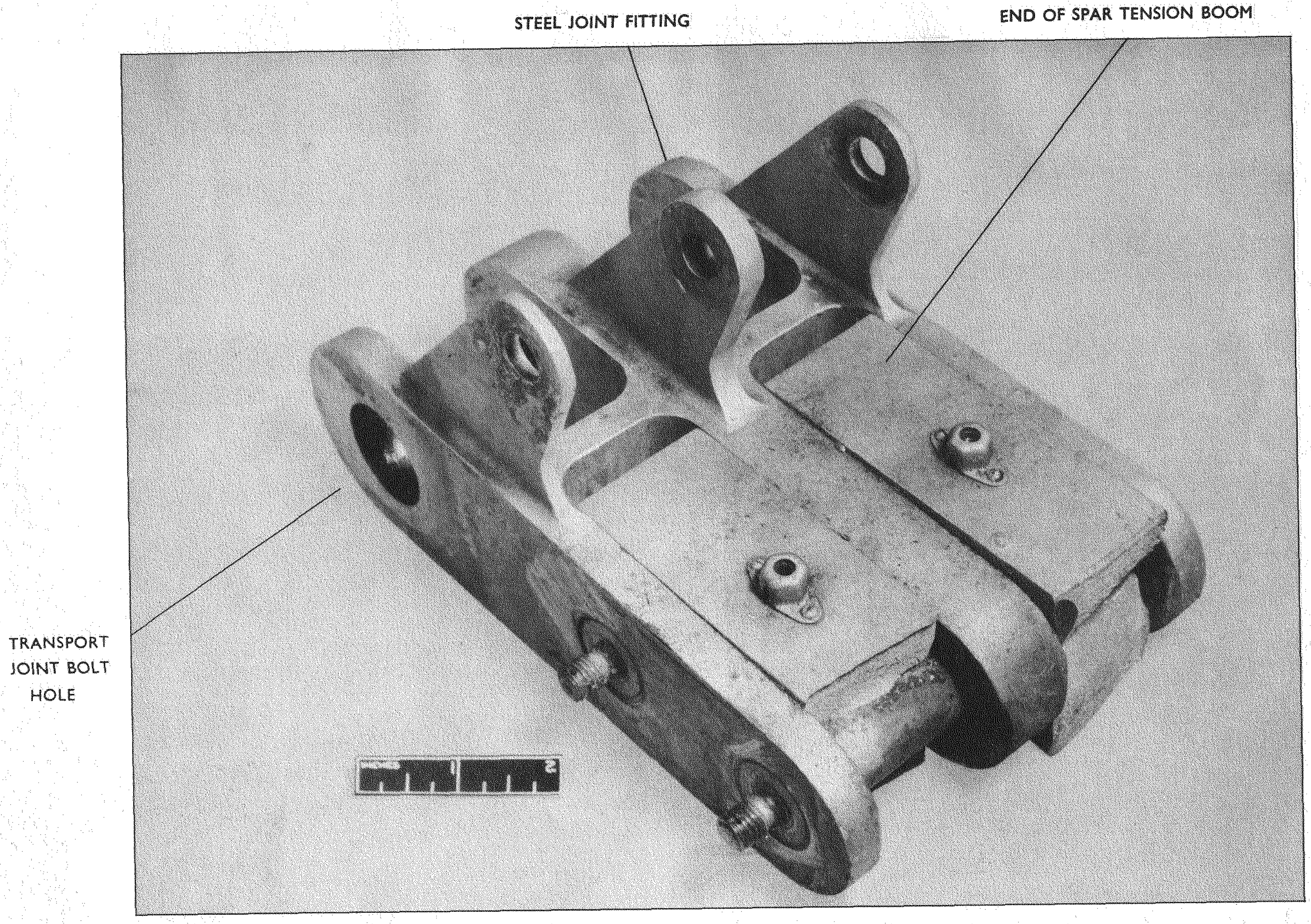

FIG.26. PORT OUTER WING JOINT FRACTURE, THIRD TEST

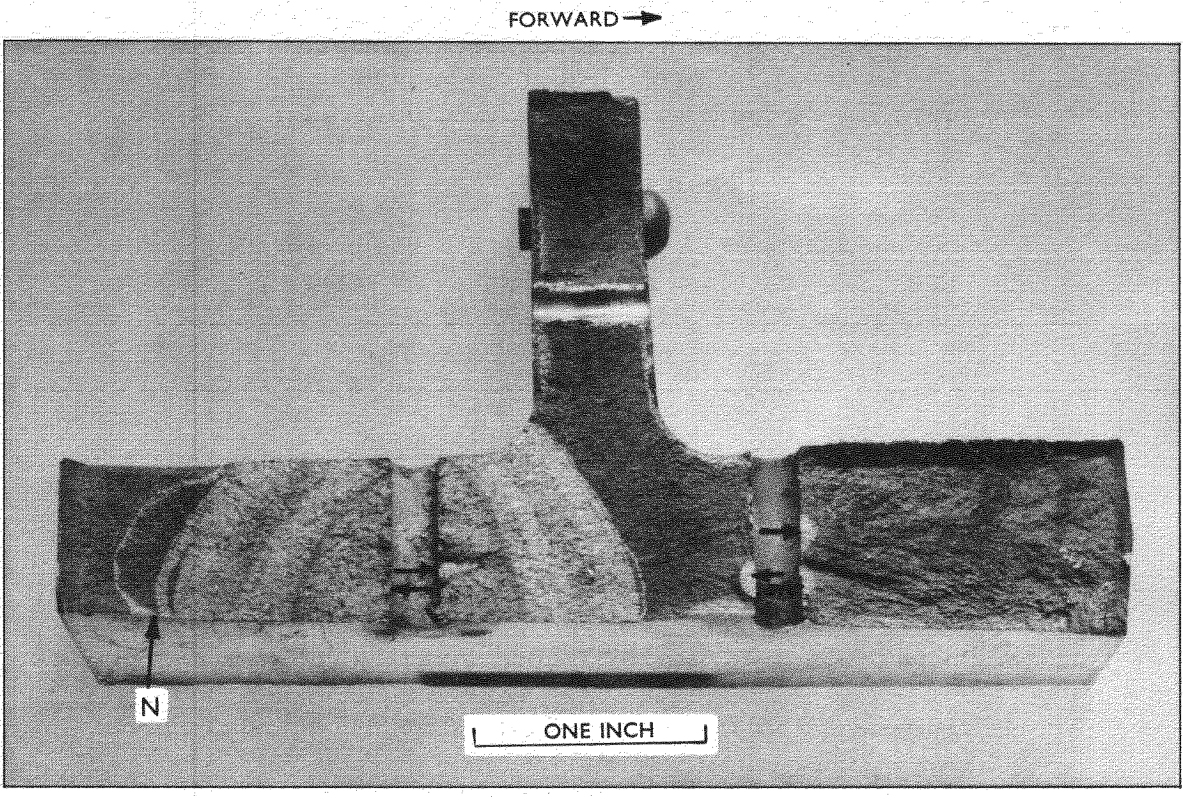

FIG.31. STARBOARD OUTER WING, FOURTH TEST

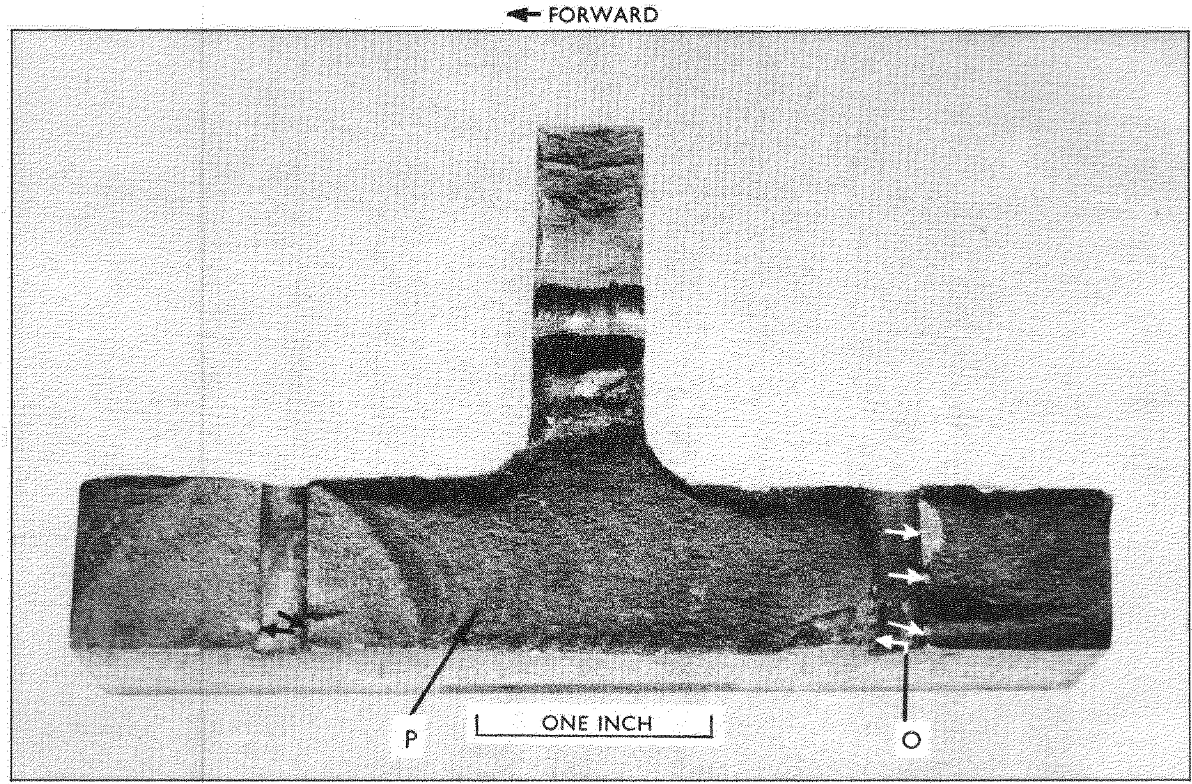

FIG.32. PORT OUTER WING, FOURTH TEST

FIG.31 & 32 TENSION BOOM FRACTURES

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